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Direct Back-Emf Detection Methods for Sensorless Speed and Position Control of BLDC Motors

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Abstract: Brushless Direct Current (BLDC) motors are more popular due to its simple structure and no maintenance. Improvements in permanent magnetic materials and power electronic devices have resulted in reliable, cost effective BLDC drives, for many applications. BLDC motors find applications in diverse fields such as domestic appliances and automobiles due to its low cost and performance. Sensorless means fewer parts, i.e. the omission of the position sensors and auxiliary decoding circuitries. High reliability, cost reduction and compactness are main advantages of sensor less strategies. The only reliable way to utilize the BLDC machine drives in harsh environments is sensor less techniques. For sensor less control Direct back-EMF detection and Indirect back-EMF detection methods are used, in this paper we will discuss Indirect back-EMF detection methods. In this paper, various direct back-EMF detection methods are explained for sensor less speed and position control of BLDC motors, for detecting rotor position signal accurately and reliably, so that BLDC motor can commute and run correctly. Firstly, we will discuss about "back-EMF Zero Crossing Detection/Terminal Voltage Sensing Method" and Secondly, "Various PWM Strategies" for various applications.

Keywords: BLDC motor, sensor less, back-EMF, PWM, Zero Crossing Detection.

I. INTRODUCTION

Brushless DC Motor uses electronic commutation to replace the electro-brush in DC motor. It not only keeps the advantages of DC motor, but also avoids the disadvantages of DC motor caused by electro-brush. Because of its advantages such as good mechanical characteristic linearity, wide speed range, long service life, easy to maintain, high reliability, low-noise, no commutation spark, etc. it was widely used in electrical and household appliances, industrial equipment, automotive and military equipment is widely applied in the field. In DC commutator motor, current polarity is altered by commutator and brushes. In the BLDC motor polarity reversal is performed by power transistors switching in synchronization with the rotor position.

To accomplish this, BLDC motor is inverter fed. Inverter is designed in such a way that, its output frequency is function of instantaneous rotor speed and its phase control will correspond to actual rotor position. In the excitation of a three-phase BLDC motor, only two of the three phase windings are conducting at a time and the no conducting phase carries the back-EMF. Directly Sensing back-EMF of this unused phase & no use of Hall sensors for detecting the speed and position of rotor make it direct back-EMF detection method. So, a BLDC motor drive that does not require position sensors but only electrical measurements is called a sensorless drive [1]. The back-EMF of floating phase is sensed and its zero crossing is detected by comparing it with neutral point voltage. Another back-EMF sensing methods which does not require a virtual neutral point and large amount of filtering are Various PWM Strategies for various applications.

II. MATHEMATICAL MODEL

In the figure 1 [2], three inverter phases are shown in a different colour: red phase A, green phase B, blue phase C, and pink neutral point N. The initial position of the rotor is determined by non-linear magnetic saturation characteristic of stator iron. The inductance of stator winding is a function of the rotor position because when the stator winding is excited, applying a DC voltage for a certain time, a magnetic field with a fixed direction will be established. Then, the current responses are different due to the inductance difference, and this variation of the current responses contains the information of the rotor position [3].

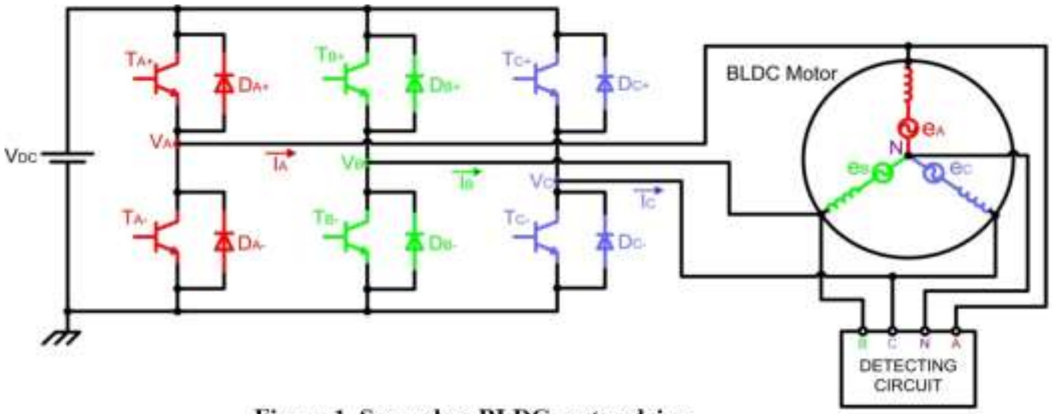

Figure 1. Sensorless BLDC motor drive

The study of the circuit shown in Figure 1 is based on the BLDC motor model for phase A, shown in Figure 2 and the following assumptions are considered [4]:

1. The motor is not saturated
2. Iron losses are negligible
3. Stator resistances of all the windings are equal (Rs)
4. Self-inductances are constant (Ls)
5. Mutual inductances (M) are zero

Now, voltage function of the conducting phase winding might be expressed as indicated in Equation (1):

VDC = I.Rs + Ls.dI/dt + e (1)

Where, VDC = DC voltage.

Rs & Ls = equivalent resistance and inductance of stator phase winding respectively.
e = trapezoidal shaped back-EMF.

III. BACK-EMF ZERO CROSSING DETECTION (ZCD) METHOD

Back-EMF Zero Crossing Detection (OR Terminal Voltage Sensing) is one of the simplest methods of back-EMF sensing technique, and is based on detecting the instant at which the back-EMF in the unexcited phase crosses zero. Using a six-step commutation technique through a three-phase inverter for driving the BLDC motor as shown in Figure 1, the conducting interval for each phase is 120 electrical degrees. Therefore, only two phases conduct current at any time, leaving the third phase floating whose back-EMF is sensed and its zero crossing is detected by comparing it with neutral point voltage.

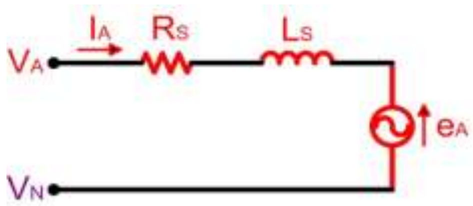

Figure 2. BLDC motor model for phase A

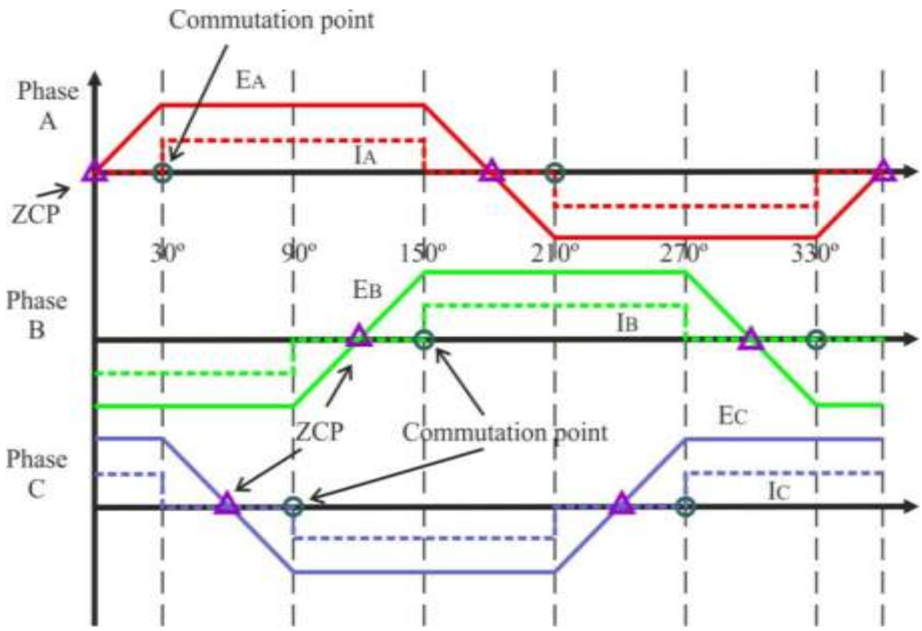

Figure 3. Zero crossing points of the back-EMF and phase current commutation points

The current commutation point shown in Figure 3 can be estimated by the zero crossing point (ZCP) of back-EMFs and a 30° phase shift [1]. The inverter should be commutated every 60° by detecting zero crossing of back-EMF on the floating coil of the motor [4], so that current is in phase with the back-EMF to produce maximum torque. When particular phase current is zero the back-EMF is determined and zero crossing points detected. Due to inverter switching higher harmonics produced in the phase terminal voltages so three low-pass filters used. Low-pass filters will limit the high speed operation capability due to their time-delay characteristics.
Zero-crossing point detection formula can be calculated from Figure 1 and shown in Equation 2. The terminal voltage of the floating phase is given as:

$$V_{CE}^{A+} \approx V_{CE}^{B-} \Rightarrow V_C = e_C + \frac{V_{CE}^{B-} + V_{DC} - V_{CE}^{A+}}{2} \approx e_C + \frac{V_{DC}}{2} \quad (2)$$

Where eCis the back-EMF of the opened phase (C), VB=VCE (collector-emitter voltage of transistor TB-)
Zero-crossing occurs when the voltage of the floating phase reaches one half of the DC rail voltage [3]. The end of the PWM on-state is noise free so chose for the zero-crossing detection point. At low speeds or at standstill, back-EMF is detection method cannot be applied well because back-EMF is proportional to the motor speed. In critical applications, such as aviation systems a starting procedure used to correct start-up the motor from standstill [4].

At high speeds, the long settling time of a resonant between the motor inductance and the capacitance of MOSFETS can cause false ZCD points of back-EMF. To avoid this problem- detect the back-EMF during on time at high duty cycle [5], so there is enough time for the resonant transient to settle down.The terminal voltage sensing method is widely used for low cost industrial applications such as fans, pumps and compressor drives where frequent speed variation is not required.

IV. PWM STRATEGIES

Various type of PWM techniques used for direct back-EMF detection for sensorless speed and position control of BLDC motors. In this section, we will discuss Conventional 120º PWM strategy, Virtual Neutral Point Elimination Technique and Direct Current Controlled technique, Improved PWM technique for small power applications, Complementary PWM method.

A. CONVENTIONAL 120° PWM TECHNIQUE

Circuit in Figure 1 controlled by the PWM technique to give proper sequence of commutations so that two phases are with ON states and the third one phase is with floating state. Now, the inverter performs the functions of brush and commutator in a conventional DC motor, to generate a rotational stator flux [2,6]. PWM waveforms for 120° Conventional techniques are shown in Figure 4. In the conventional approach, 120° PWM method is used where the conducting interval of each phase is 120° electrical angle as shown in Figure 4. In order to produce maximum torque, inverter should be commutated every 60°, so that the current is in phase with the back-EMF. This method has merit of low switching losses in the inverter side but posse's high harmonic content which results in increase in loss on the motor side.

B. VIRTUAL NEUTRAL POINT ELIMINATION TECHNIQUE

The zero crossing of the back-EMF can be obtained by comparing the terminal voltage of floating phase to the neutral point as shown in Figure 5.In 120° conventional PWM technique the virtual neutral point fluctuates at the PWM frequency which results in very high common-mode voltage and high-frequency noise. To eliminate these problems voltage dividers and low-pass filters are used, as shown in Figure 5.

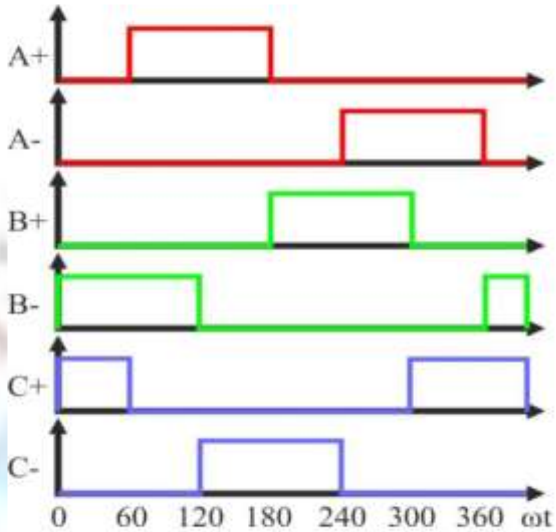

Figure 4. 120° PWM Conventional Waveform

Now, Virtual Neutral Point elimination technique means when measuring back-EMF, no filtering is required and zero crossing points of the back-EMF voltage of the floating phase can be obtained directly from the motor terminal voltage referred to ground.In this method the PWM signal is applied on high side switches only, and the back-EMF signal is synchronously detected during the PWM off time [7], as shown in Figure 6.The low side switches are only switched to commutate the phases of the motor. Then, the true back-EMF can be detected during PWM off time because the terminal voltage of the motor is directly proportional to the phase back EMF during this interval.

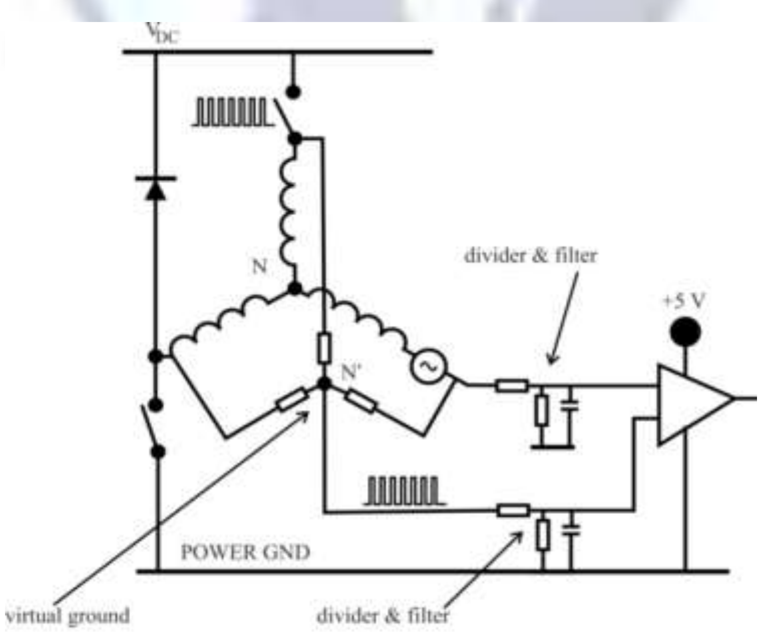

Figure 5. Virtual Neutral Point ckt. for back-EMF Detection

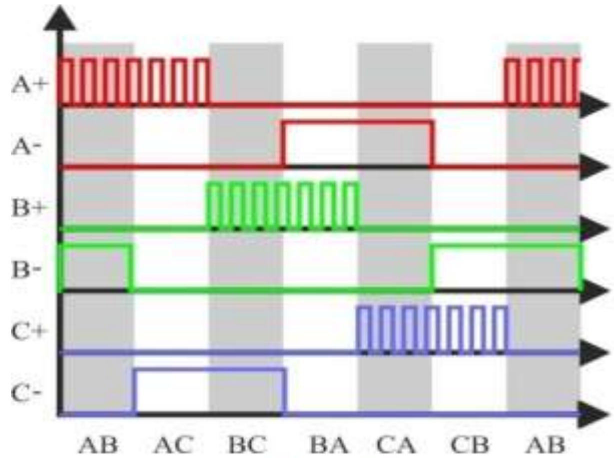

Figure 6. PWM applied to HIGH side switches for direct back-EMF detection in Neutral Point Elimination method

Terminal voltage is referenced to the ground instead of the floating neutral point, so the neutral point voltage information is not needed to detect the back-EMF zero crossing [8]. The resulting signal is not attenuated or filtered and it has a good signal/noise ratio, including a much wider speed range.

C. DIRECT CURRENT CONTROLLED PWM TECHNIQUE (HYSTERESIS CURRENT CONTROL)

The direct current PWM control technique is based on the current controlled PWM method, instead of the voltage controlled PWM, which generates robust speed and torque responses and is simple to be implemented from the hardware and software points of view. One switch leg of BLDC motor drive as shown in Figure 1 is replaced with a split capacitor pair as shown in Figure 7. In this technique, two phases are connected to the switch legs and the other phase to the midpoint of DC-Link capacitors. But, the limited voltages make very difficult to obtain 120° conducting profiles. This is the well-known problem asymmetric voltage PWM [4], which results in the 60° phase-shifted PWM strategy to generate three-phase balanced current profiles. In a PWM control strategy for the four-switch three-phase BLDC motor drive, the three-phase currents always meet the condition of Equation (3):

$$Ic = -(Ia + Ib) \qquad (3)$$

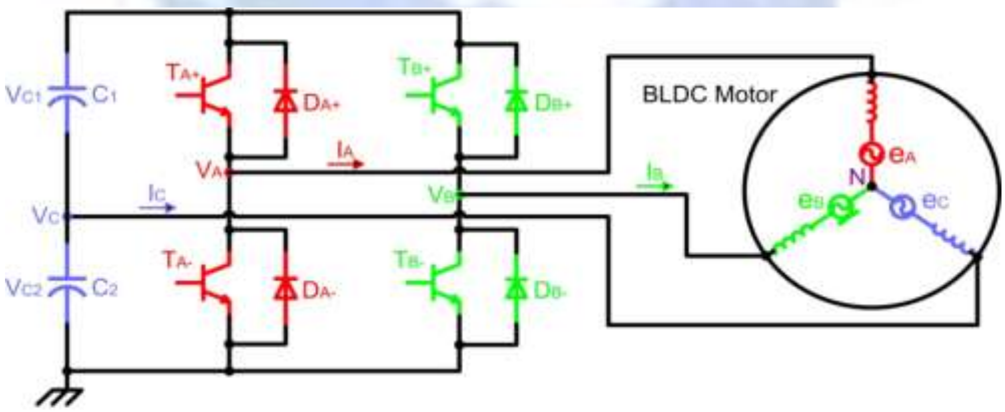

Figure 7. Four-switch converter for driving a three-phase BLDC motor using Direct current controlled PWM techniques

Hence, control of the two-phase currents can guarantee the generation of the 120º conducting three-phase currents profiles. The two-phase currents are directly controlled using the hysteresis current control method by four switches.

D. IMPROVED PWM TECHNIQUE FOR SMALL POWER APPLICATIONS

For small power applications of BLDC drives power consumption reduction is the main objective because of the use of battery and limited space for heat dissipation. In the PWM technique presented by Yen-Shin Lai et al. [7] the high side power device is chopped in 1/6 fundamental period, duty ratio is derived from the speed reference or error of speed. For the next 1/6 fundamental period, it is clamped to positive dc link for both intervals of high side device, the associated low side device is off as shown in Figure 8. Similar control signals are given to low side devices with 180° shift.

However as the low side device is on, output terminal is connected to the negative dc link. For other two phases the control signals are applied with 120°shift.As the high-side device is with chop control, the associated low-side power device is triggered by the inverse signal of chop control. To highlight the feature of this PWM technique, the voltage drop caused by the turn-on resistance of power device and load current is significantly reduced as compared to the forward voltage drop of diode. Therefore, the power consumption and the heat losses can be significantly reduced.

E. COMPLEMENTARY PWM METHOD

Technique for low speed or low voltage applications, the voltage drop across the BJT's or MOSFET's will affect the performance. When the motor speed goes low, zero crossing is not evenly distributed. Besides, if the speed goes further low, the back-EMF amplitude becomes too low to detect [7].There are basically two methods to correct the offset voltage of back-EMF signal. One of them is to use complementary PWM as shown in Figure 9, which also reduces the conduction loss. Another method is to eliminate the effect of diode voltage drop in order to add a constant voltage to compensate the effect of diode, and threshold voltage for avoiding the asymmetry in the distribution of zero crossing [5]. Then, in order to eliminate the non-zero voltage drop effect, a complementary PWM can be used, which will also reduce the power dissipation in the devices [5].However, at low speed especially during the start-up, the back-EMF itself is very small so an amplifier can be used as a pre-conditioning circuit.Finally, the motor speed can be greatly expanded with the improvements explained before.

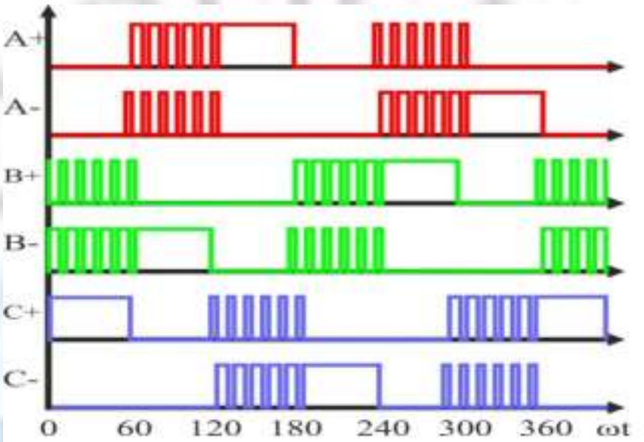

Figure 8. PWM scheme with reduces power loss

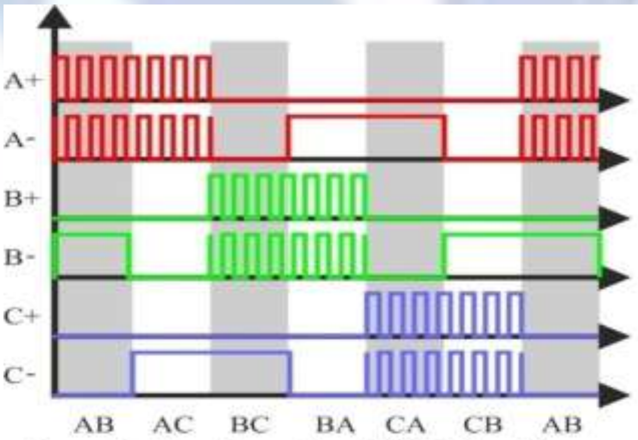

Figure 9. Complementary PWM algorithm

V. CONCLUSIONS

A complete review of direct back-EMF detection for sensorless control of BLDC motors is presented. Since back-EMF is zero at standstill and proportional to speed, the measured terminal voltage that has large signal-to-noise ratio cannot detect zero crossing at low speeds. That is the reason why in all back-EMF-based sensorless methods the low-speed performance is limited, and an open-loop starting strategy is required [8].

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